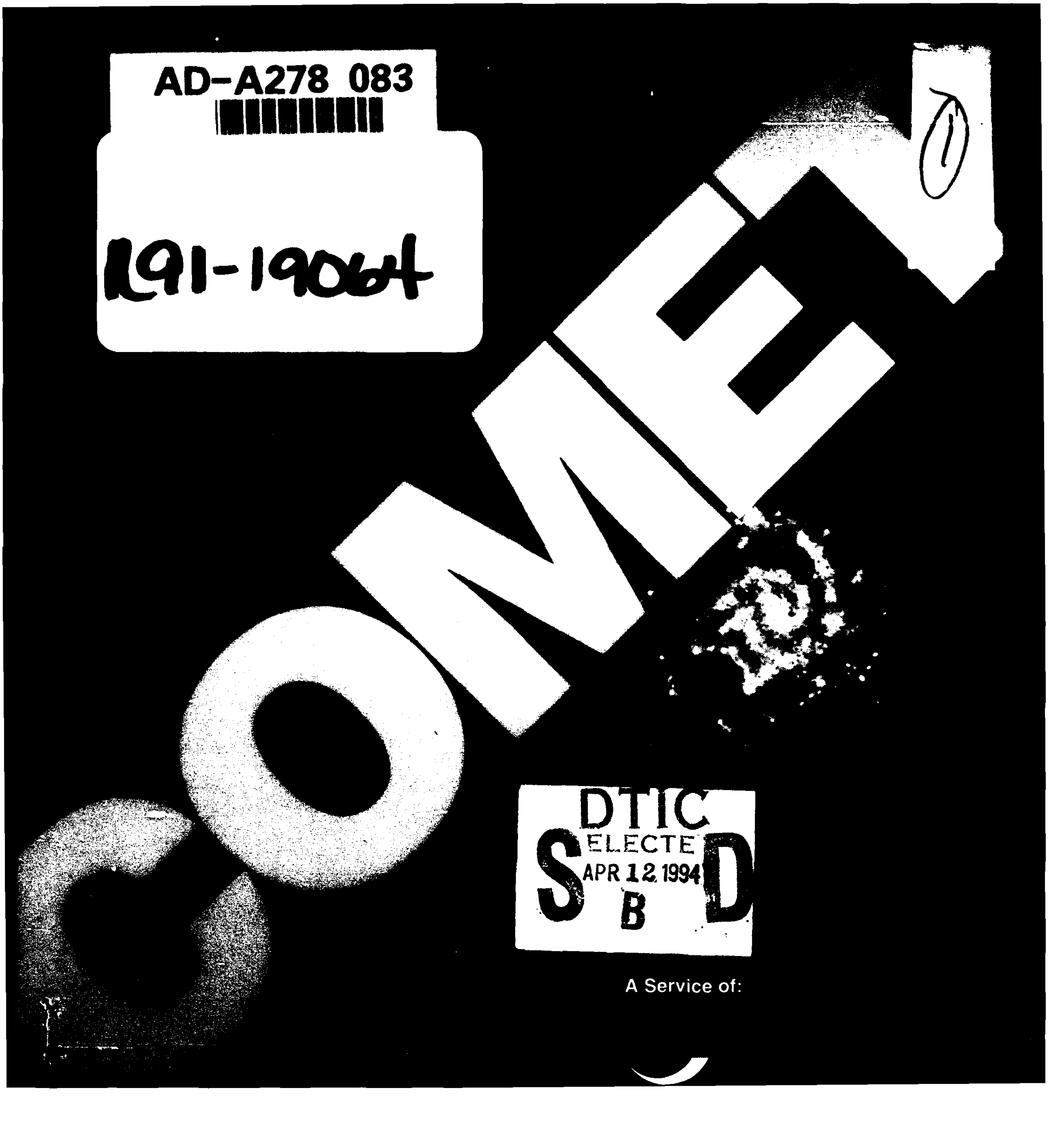

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THE DEVELOPMENT OF A RAM AIR DECELERATOR FOR THE RECOVERY OF ARTILLERY SHELLS

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Abstract

Sandia National Laboratories is responsible for the design of recovery systems for atomic artillery shells that are periodically tested by artillery firings. It is desirable to have a recovery system that exhibits a high degree of reliability due to the costs associated with each test shell. A Ram Air Decelerator (RAD) has been investigated as a candidate replacement for the current parachute recovery system. Tests have included proof-of-concept tests on a truck towing rig, non-spinning airdrop tests, spin tests in a high altitude chamber and artillery fired projectile tests. Although testing had to be terminated before the program could be completed, significant strides were made in RAD design for this harsh environment. Possible design improvements were identified for future testing should the program be revived.

Introduction

Sandia National Laboratories is responsible for the design and testing of atomic artillery shells. During the development and the continued stockpile evaluation of a type of shell, numerous artillery test firings are conducted. In many of these test firings, it is necessary to recover the shell intact to evaluate the performance of its components. In flight, the shells are spin stabilized and can be revolving at more than 15,000 rpm (250 rps). To permit recovery, they are fired from guns set at high quadrant elevation angles 85° to 88° above the horizontal. On such high trajectories, the shell falls base first after passing apogee.

Presently, a parachute recovery system[1] is being used to reduce the velocity of the shell before impact. During descent, while the shell is suspended on the parachute and spinning at a high rate, aerodynamic and gyrodynamic forces can cause it to nutate to a large enough angle that the shell turns nearly upside down. This can result in the shell rubbing on the lines which connect it to the parachute and can cause a failure of the recovery system. The spin of the shell is decreased only by air friction, friction in the swivel and friction between the shell and the lines when they rub. A shell recovered with the present parachute recovery system can still be spinning at more than 5,000 rpm when it impacts the ground. Although the present recovery system has been developed to the point that it provides better than an 85% success rate, it is very desirable to further improve the recovery system reliability because of the cost of each test item.

The term Ram Air Decelerator (RAD) normally refers to a device with a closed pressure boundary (with the exception of the ram air inlets) that is inflated by ram air. A RAD is typically constructed of a bottom fabric panel and a top fabric panel that are fastened together along their outer edges to form a closed container. The only intended openings into this container are the ram air vent holes located in the bottom panel. Figure 1 shows a sketch of an inflated four-lobe RAD attached to an artillery shell. RADs offer a possible advantage over a parachute recovery system because they can be mounted directly on a shell. Thus, if the shell tries to nutate to a base upward position, the RAD will nutate with it and continue to de-spin the shell through torsional air drag. No rubbing or contact damage will occur since there is little or no relative motion between the RAD and the shell. The capability to mount the RAD directly on the shell can also eliminate the need for high speed swivels which are used in the present parachute system to preclude winding up and collapsing the parachute. However, this means the RAD must be capable of withstanding the centrifugal loads and the torsional drag generated in the RAD when it is initially deployed. A schematic of a typical flight profile is shown in Figure 2.

Existing RAD designs for submunition applications[2] typically have characteristic lengths (center of RAD to the tip of lobe) of less then six inches. The size of the RAD required is driven by the payload weight, the desired impact velocity, and the RAD's coefficient of drag. The weight of the artillery shell intended for recovery is approximately 90 lbs. The maximum impact velocity desired is less than 220 fps. This requires a RAD with a diameter of 30 to 36 inches.

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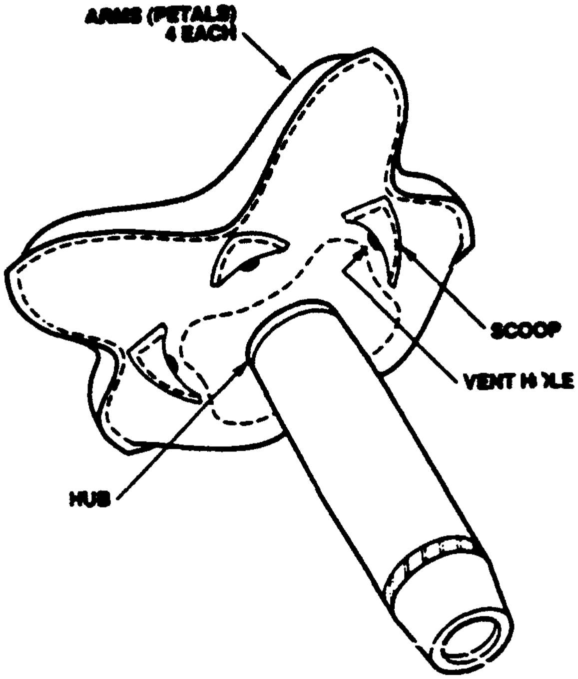


Figure 1
RAD Attached to an Artillery Shell

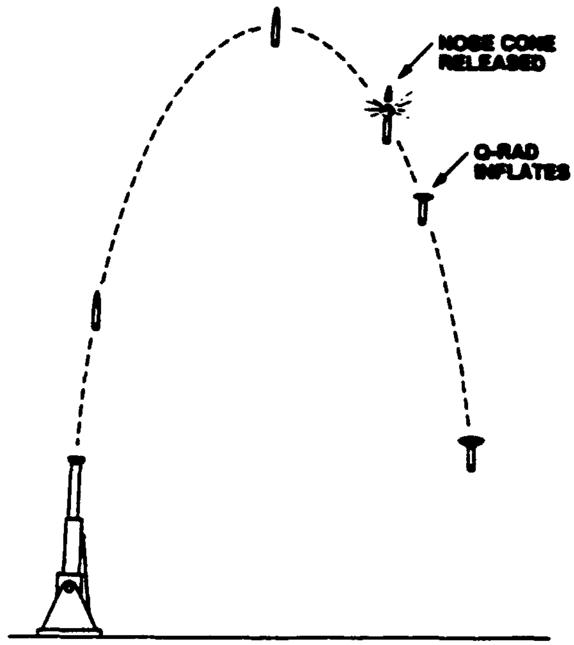


Figure 2
Flight Profile for Artillery Shell Recovery

Flight Simulation

No ground test facility exists which can simultaneously simulate the entire environment that an artillery-recovering RAD would experience. However, different aspects of the environment can be simulated individually.

Spin Tests

One of the most severe aspects of this environment is the large spin rates. For the rather large characteristic dimensions required for the RAD to be used for artillery shell recovery, very large forces develop in the RAD due to centrifugal loads. Thus it was desirable to test the RADs in this extreme centrifugal loading environment. Spinning a RAD at these rates in a standard atmosphere would produce a very large torque on the RAD due to aerodynamic drag. More could be learned about the centrifugal component of the load in the absence of these aerodynamic loads. Thus, Sandia's High Altitude Chamber (HAC) was employed.

The HAC is a 27-ft diameter spherical pressure vessel capable of reaching a 200,000-ft equivalent pressure altitude in about 30 minutes and maintaining it indefinitely. A high speed spin test apparatus was designed, fabricated and installed in the HAC, thereby allowing spin tests to be conducted with virtually no aerodynamic drag present. The spin apparatus utilized an air turbine and RAD attachment spin hardware capable of spinning up to 30,000 rpm (500 rps). A control system regulated the supply air to the turbine to maintain the desired spin rate and employed over-speed protection logic to automatically disconnect the turbine from the supply air in the event of RAD failure. A failsafe coupling was designed into the RAD mounting hub to allow the RAD to fly away from the spin rig if out-of-balance conditions exceeded safe limits. An accelerometer allowed the monitoring of vibration levels. A schematic of the spin apparatus as installed in the HAC is shown in Figure 3. The tests were monitored with two remotely controlled video cameras (pan/tilt/zoom) and two high speed (400 pps) movie cameras mounted inside the HAC and a high speed (1000 pps) video camera viewing through a window from outside the HAC.

Tow Tests

An aspect of the RAD that can be investigated independently from spin is the inflation characteristics. Many means for evaluating this are available including wind tunnel and flight testing. However, these are typically time consuming and costly. A cheaper and more timely method of investigating qualitatively the inflation characteristics was desired. A device was designed and fabricated which would fit onto the bed of any pick-up truck and provide a means of testing up to dynamic pressures of 15 psf. The device consisted of a framework of Unistrut that fit into the two stake holes of the bed and a mast that protruded approximately 17 ft above ground level. A pivot at the base of the mast allowed it to be raised and lowered easily. Various cables and spreader bars were used to obtain a more rigid structure. This rig can be seen in Figure 4.

The RAD was attached to a forebody which was mounted on the mast. The forebody simulated an artillery shell. A deployment bag was initially installed over the RAD and the forebody. A 4-ft-dia guide-surface parachute was attached to the deployment bag. A video camera was attached

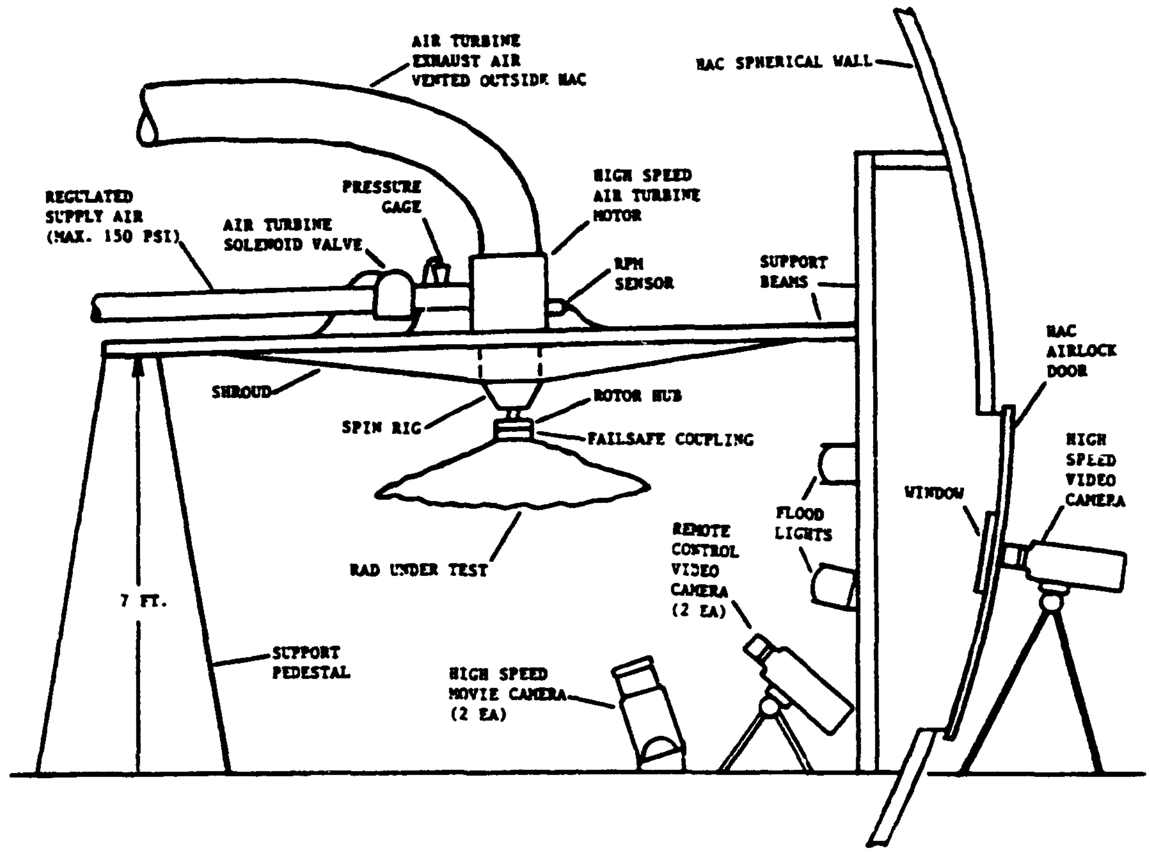


Figure 3
Schematic of the RAD Spin Apparatus

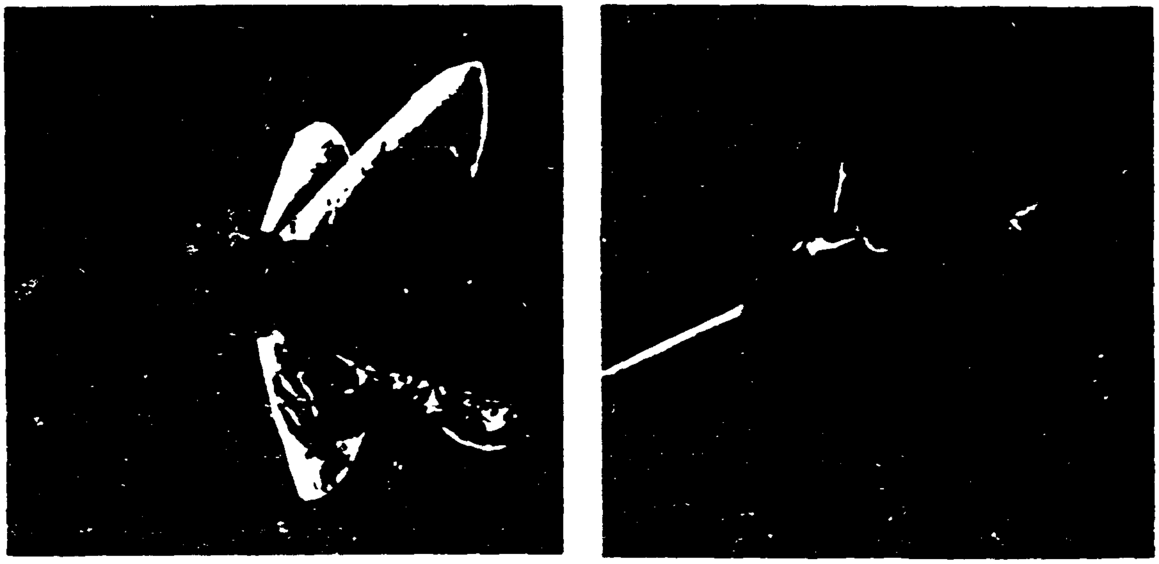
to the mast to view and record the RAD during the test. The camera had tilt, pan, and zoom capability which was controlled remotely by a person in the cab of the truck. A typical test involved accelerating the truck, releasing the deployment bag at some point during the acceleration phase and then maintaining a desired speed briefly while observing the RAD. In this manner, qualitative information on inflation could be gathered and recorded very quickly. Figure 5 shows two views of a RAD in its inflated shape while on the mast of the tow test rig.

Figure 4
RAD Tow Test Rig

Air Drop Tests

The spin and tow tests proved to be very cost effective. Required resources were limited to personnel assigned directly to the program. Scheduling of the facilities was virtually never a problem. However, these tests could not verify terminal descent drag areas or velocities. Therefore, a third method of testing was employed -- air drops from a helicopter.

The same deployment bag used for the tow tests was used for the airdrop tests. Three vehicles weighing 25, 55, and 95 lbs respectively were used. The 95 lb vehicle was a dummy artillery shell that simulated the ultimate RAD payload. The tests were conducted by installing the vehicle and the RAD into the deployment bag that was attached to a lifting hook underneath the helicopter. The helicopter would ascend to the



a) Bottom View b)Top View

Figure 5
Inflated Shape of QRAD

desired release altitude and maintain a minimal forward velocity. Reflective tape on the front of the test vehicle protruded through the bottom of the bag and allowed a ground-based laser-tracker to lock onto the vehicle. Upon command from the ground, the bottom of the deployment bag was opened allowing the vehicle to fall trailing the RAD. As the vehicle accelerated, the RAD inflated and the vehicle approached a terminal descent velocity. During the entire time of fall, the laser-tracker followed the vehicle and computed location and velocity data. Several video and high-speed film cameras recorded the event. These tests verified the inflation characteristics and produced drag area and terminal velocity data. The tests were more costly and harder to schedule than the spin and tow tests, but were a necessity before proceeding in the test program.

Artillery Tests

The only means of testing in the complete environment were to fire a test vehicle as an artillery shell. Such tests were possible at Sandia's Tonopah Test Range (TTR), Nevada. At TTR several 155 mm and 8 inch artillery guns are available to fire a shell at high elevation angles. Upon using a full propulsive charge, the shell reaches an apogee of approximately 70,000 ft. Radars and optical telescopes are able to track the shell; however, photographic coverage is impossible at these extreme altitudes. A wide range of propulsive charges is available that produce apogees as low as 25,000 ft. These low charges also produce lower spin rates resulting in lower centrifugal loads in a RAD as it deploys. However, even though the spin rate is reduced, the increased density at the lower altitude results in larger aerodynamically produced torques on a RAD. Thus, it is not clear which environment is the more severe. This facility was used in the last stages of the test program for combined effects testing.

Test Program

Phase I

The initial design of a RAD for the artillery shell recovery system used a 20 inch diameter three-lobe RAD, designated TRAD. The shape of the TRAD was specified by Alex T. Zacharin[3]. Two TRADs were fabricated using single layers of coated Kevlar cloth for both the top and bottom panels. These TRADs were mounted on three different drop test vehicles that had weights of 25, 55, and 95 lb. The tests involved dropping the vehicles from a helicopter. In each of these tests the TRADs inflated very quickly and produced a controlled descent. The 95 lb vehicle, a mockup of an actual 155 mm artillery shell, reached a descent velocity of approximately 200 fps at ground impact at an altitude of 5300 ft.

Spin tests were then conducted in a high altitude chamber (described previously) to evaluate the ability of the TRAD design to withstand the high centrifugal loads. A review of the strength and density properties of several candidate materials, see Table 1, showed Kevlar offers the greatest strength to weight of any of the readily available filament materials.

The first spin tests of the three-lobe designs using woven Kevlar fabric showed that the three-lobe RADs had special problems when subjected to severe centrifugal loads. The very nature of a three-lobe design constructed from a single layer of fabric resulted in the weave orientation (straight or bias) of the fabric differing from lobe to lobe. Thus, the lobes did not strain uniformly as the unit was centrifugally loaded by the spin. This produced an unbalanced behavior and ultimately contributed to the self-destruction of the unit. This

Table 1
Candidate Material Properties

Material	Tensile Strength, σ_T (ksi)	Density, ρ (slugs/ft^3)	Strength to Weight Ratio σ_T/ρ (ksi ft^3/slug)
Polypropylene	5.	1.7	2.9
Nylon	11.	2.2	5.0
Steel	200.	14.7	13.6
Kevlar	520.	2.8	186.

first series of spin tests indicated that the lobes should be aligned with the warp and fill directions of the orthogonally woven fabric to take full advantage of the Kevlar filament strength.

Phase II

Drawing from the experience gained from the spin tests in Phase I, a TRAD was constructed with each lobe cut from the Kevlar fabric so that the warp yarns aligned with a radial line drawn from the center of the hub to the tip of a lobe. Recognizing that the coating on the Kevlar cloth used in the Phase I TRADs added considerable weight with little or no increase in strength, uncoated Kevlar cloth was used in Phase II. The three lobes were sewn together along radial lines projecting from the center outwards midway between the tips of each of the lobes. When spun, these seams proved to be a weak spot and again the TRAD was destroyed.

When the top and bottom panels of a RAD are constructed with single layers of fabric, the stress in the fabric due to centrifugal loads varies as a function of the square of the radial distance from the outer edge of the RAD. To reduce the fabric stresses, the number of filaments carrying the load was increased by adding layers of fabric to each panel as an inverse function of the radial distance from the center of rotation, the hub. This method of fabrication approximated one used in modern high-speed flywheel designs. A second TRAD was fabricated using this method with three fabric layers in the hub region, two layers in the intermediate region and one layer in the tip region. Each lobe was aligned with the warp filaments (yarns) of the fabric. This construction eliminated the need for the radial seams of the earlier Phase II design and improved the overall performance of the TRAD. However, the ultimate spin rate goal of 250 rps could not be met.

To further improve the filament loading efficiency of the ram air decelerator design, a change to a four-lobe design was made. This four-lobe RAD design was designated as the Quadripetal Ram Air Decelerator (QRAD). The four-lobe design offered a larger projected area of inflated fabric to the flow than did the three-lobe design (about 16 percent increase) for the same lobe tip radius. This gives a QRAD more drag for the same tip radius than a TRAD.

As different size TRADs were constructed in the program to develop a RAD recovery system for an artillery shell their patterns were simply obtained by scaling the Zacharin patterns[3]. When the decision was made to build four-lobe QRADs a method had to be devised to define the patterns for the top and bottom panels and for the added reinforcing layers of fabric. Zacharin had defined the shape of the top and bottom panels of TRADs by a series of arcs. The same type of procedure was used to define the panel shapes for the QRADs. Figure 6 shows a design cross-section of a QRAD.

The exact shape of the QRAD panels, such as the depth of the valley between lobes, the shape of the lobe, and the height of the cross-section, was developed by a trial and error process where prototypes with differing proportions were constructed and evaluated. Once, the shape and size of the top panel were selected, the dimensions of the bottom panel were constrained so that the length of the outer edge of the bottom panel would closely match that of the top panel. This constraint was necessary since the top and bottom panels had to be joined by stitching along their outer edges.

A computer code was formulated to perform the iterative process that was required to match the length of the outer edges of the bottom panel to that of the top panel. Input to the code is shown in Table 2 and illustrated in Figures 6-8. The code calculated the parameters needed to construct the top panel and the parameters needed to construct a bottom panel that met the edge length requirement.

Table 2
QRAD Sizing Parameter Definitions

Parameter Name (see Figures 6, 7 & 8)	Parameter Definition
R_x	maximum radius
R_b	hub radius
H	height parameter
Δ	seam width
X_o, Y_o	lobe shape parameters
β	inclination of straight section

It also calculated the outer radii for each reinforcing fabric layer that was to be used. The outer radii for the reinforcing layers are defined so the maximum stress at the hub due to centrifugal loads is not greater than the maximum at any other radius in the panel. Figure 9 shows the advantages of using reinforcing layers of fabric. When no reinforcing layer is used in the panel the stress increases monotonically as the hub is approached. By inserting reinforcing layers at the various radii the maximum stress experienced by the fabric can be controlled. This is illustrated by the second curve where two

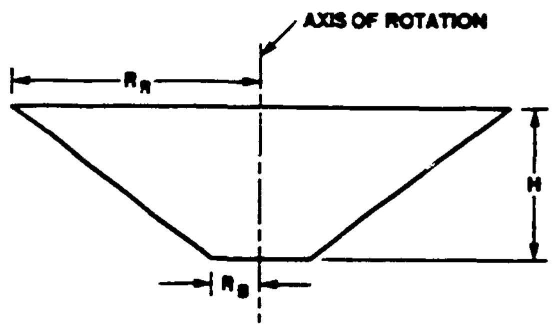


Figure 6
Cross-section Profile of QRAD

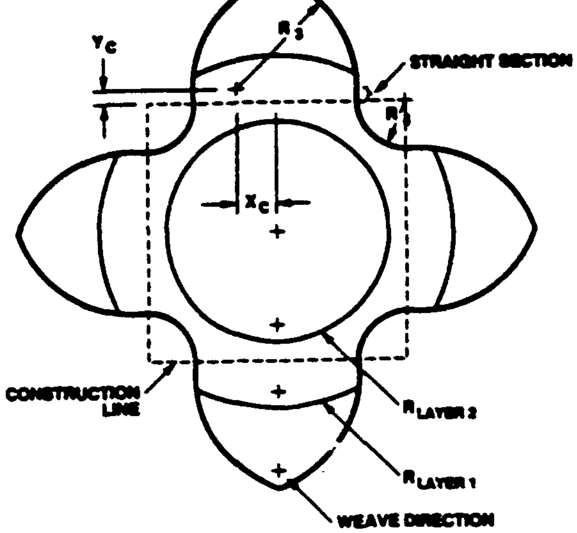


Figure 7
QRAD Top Panel

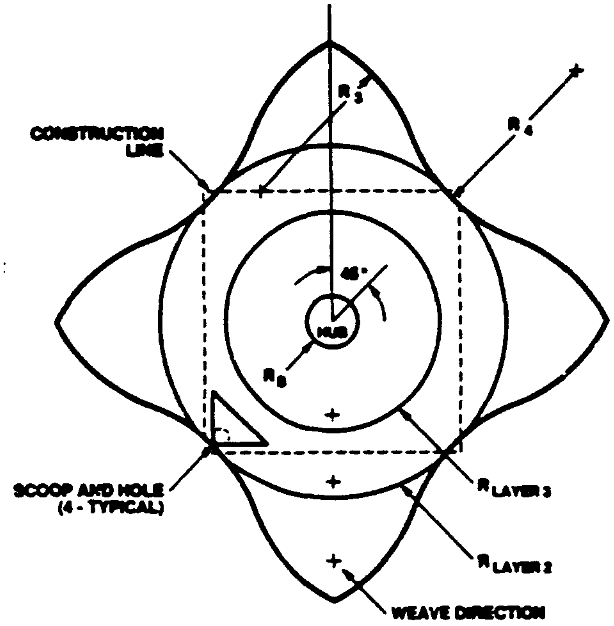


Figure 8
QRAD Bottom Panel

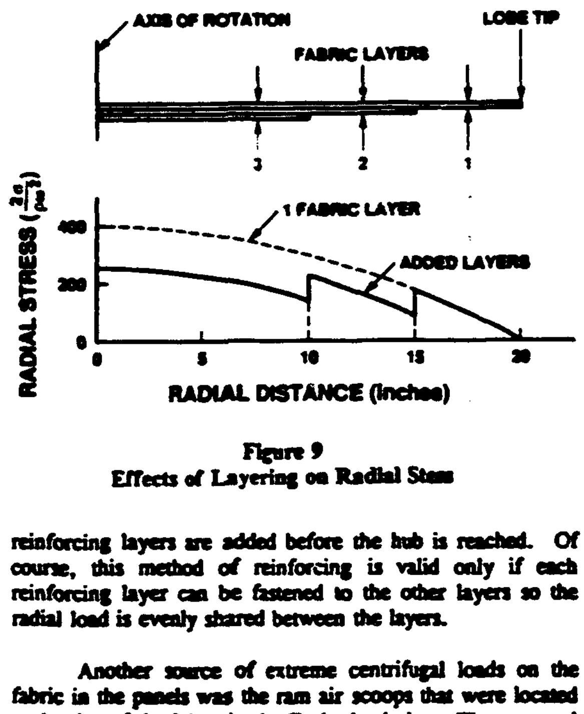


Figure 9
Effects of Layering on Radial Stess

reinforcing layers are added before the hub is reached. Of course, this method of reinforcing is valid only if each reinforcing layer can be fastened to the other layers so the radial load is evenly shared between the layers.

Another source of extreme centrifugal loads on the fabric in the panels was the ram air scoops that were located at the tips of the lobes in the Zacharin design. These served as concentrated masses and could not be tolerated at the large tip radii. The scoops were moved from the tips of the lobes to the troughs between each of the lobes. Locating the scoops much closer to the hub greatly reduced the centrifugal loads in the scoop attachment regions.

The QRAD design with the ram air scoops located in the troughs proved very promising in the spin tests, surviving up to spin rates as large as 270 rps (16,000 rpm). Figures 7 and 8 are sketches of top and bottom panel designs that show the design parameters that are output.

Several of these QRADs were built from uncoated Kevlar fabric and tested in non-spinning airdrops from a helicopter as discussed previously. None of these inflated fully and their drag performance was very poor. This poor inflation was caused by increased permeability resulting from the change to uncoated fabric and the extensive zig-zag stitching used during fabrication. These tests demonstrated conclusively that the net permeability of a ram air inflated decelerator must be small to ensure proper inflation and performance. In the construction of succeeding QRADs a lower permeability fabric was used and more attention was paid to minimizing the holes left by the stitching process.

Phase III

There are a number of different solutions for the permeability problem. One can coat an existing material, find a less permeable material, laminate an impermeable material, or install an impermeable bladder within the RAD. Most coatings that will reduce the permeability significantly, also add significantly to the weight of the material – something that we had already seen as detrimental in this application. In addition, as the parent material deformed under the extreme loads, a coating may be damaged leaving the fabric more permeable. The permeability of woven fabric is generally too great for this application. Mechanical alteration after weaving (calendering) would likely lose its effectiveness when the cloth deformed under stress. A bladder within the QRAD, if not attached structurally to the QRAD, would have to withstand nearly the same amount of stress as the QRAD itself. Thus, a laminated fabric was pursued.

The fabric of choice was the same Kevlar cloth laminated to a 0.5 mil layer of Mylar. The Mylar (plus adhesive) added little weight to the parent Kevlar cloth, would deform with the Kevlar, and rendered the Kevlar cloth nearly impermeable. Also, this laminated fabric when used to construct a QRAD, exhibited greater weave stability and improved resistance to destruction by spin.

The change to a laminated fabric, a four-lobe design, and the moving of the ram air scoops cast uncertainty on the inflation aspects of the new QRAD design. Thus, several QRADs were fabricated using the new design for simple tow tests (as described earlier) to investigate the inflation aspects. These tests indicated good inflation performance of the new design and cleared the way for additional drop tests from a helicopter to obtain drag data. Two drop tests were conducted, one with the previously mentioned 55 lb unit and one with the 95 lb simulated artillery shell. These tests were quite successful, indicating the QRAD design was adequate to inflate, produced an acceptable terminal velocity, and withstood the centrifugal loads produced by the spinning artillery shell. However, the torque produced by aerodynamic drag was not simulated in any of these tests.

Phase IV

As mentioned earlier, short of firing a shell from an artillery gun, the complete environment experienced during deployment from a spinning shell could not be readily duplicated by any other test methods. Thus, the next step in the testing involved firing a test round from an artillery gun. A test plan involving three firings was planned. The first two firings used reduced propellant charges to decrease the centrifugal loads imposed upon the QRAD. While reduced charges ensure a lower spin rate, the apogee of the shell is also reduced by the lower muzzle velocity. This means the recovery system is deployed at lower altitudes into higher air densities. In fact, the aerodynamically produced torque on the QRAD is higher at an apogee of 20,000 ft AGL than at the maximum apogee of 65,000 ft AGL. This aspect complicates the selection of appropriate test conditions.

The first firing produced an apogee of 25,000 ft and a maximum spin rate of 5,000 rpm. When the QRAD was deployed, it separated from the shell and the shell free fell to the ground. The QRAD was not recovered, but the shell was. Post-test examination revealed the QRAD had separated in the hub region between the two attachment rings. The tear patterns observed indicated a shear failure of the adhesive between the mounting rings. The second QRAD was disassembled and re-bonded using epoxy as the adhesive. This unit was fired with the same reduced charge. This shell also separated from the QRAD and free fell to the ground. Both the shell and the QRAD were retrieved. Post-test examination revealed the QRAD had separated approximately 1-2 inches outside the attachment ring. Crease patterns on the QRAD indicated that it had twisted off. Two possibilities exist for this type of failure. The torsional loads produced by the inertia of the QRAD during the extreme torsional acceleration at firing could have caused a failure of the QRAD before it was even deployed, or the aerodynamically produced torque could have caused a failure at the time of deployment.

Unfortunately, funding constraints precluded any further development and testing of this system. However, some potential solutions were identified which could be investigated should the program be restored.

Conclusions & Recommendations

While the QRAD has not been demonstrated to survive the artillery launch environment, significant advances have been made toward that goal. The absence of any other method for testing all aspects of the environment simultaneously led to a failure mode in the artillery fired tests that had not previously been experienced.

As mentioned earlier, the QRAD seemed to have been twisted off just above the attachment rings. Thus, strengthening the bottom panel in the area around the attachment rings may alleviate the problem. Additional layering near the rings could provide this increase in strength. Materials with larger strength to weight ratios than Kevlar could be employed. Spectra was given a brief consideration in this study. The difficulty of producing a non-permeable Spectra cloth coupled with time constraints did not allow for its use. The U. S. Army Natick Research, Development, & Engineering Center is presently investigating spider silk as a revolutionary material. It shows great promise in strength to weight ratio. These two materials, Spectra and spider silk, should be considered in any future development program.

The failure mode observed was produced by torsional loads. Allowing the QRAD to rotate relative to the shell might eliminate this failure mode. However, it is desirable to de-spin the shell before impact. An analysis of the rotational energy associated with the shell suggests that a limited energy absorbing clutch could be devised to couple the QRAD to the shell. The clutch would mitigate the high torsional loads placed upon the QRAD at deployment thereby reducing the chance for failure. However, the clutch would transmit the aerodynamically developed torque in the QRAD to the shell. The clutch need not be reusable nor must it survive for a long time -- the typical time of fall being 4-5 minutes. A cursory review of materials and the space available suggests that such a clutch could be incorporated.

As mentioned earlier, it is unclear whether or not the QRAD survived the extreme torsional loads during artillery launch. If the QRAD failed in this environment (prior to deployment), it was due to the inertia of the QRAD itself resisting the spin-up. Adding a more postive means of coupling the QRAD to the artillery shell could eliminate this failure mode. Such coupling might be provided by splines or ridges inside the shell nose.

Incorporation of the ideas for increased strength in the hub area, the torque mitigating clutch, and/or load coupling in the shell nose should offer enough improvement in the design to allow the design objectives to be met.

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